R&D Proposal for (Sub) 10 Picosecond Timing Detectors at the EIC

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EIC TOF PID R&D Project Introduction and Status

In RD2013-5, we proposed exploiting the substantial development done by the LAPPD collaboration to build and test a complete system prototype based on the commercially produced Incom LAPPD MCP-PMTs and read out with a PSEC5 ASIC based FEM. The committee presciently noted that some of our proposals were premature, because we have since learned that the PSEC5 ASIC SBIR was not funded, and thus will not be deliverable on any reasonable timescale. In addition, Incom has only received their SBIR funding recently, and will have early adopter MCP-PMTs starting only in the fall of 2015.

Fortunately, this allows us to restructure the proposal to align it more within the intent of the EIC R&D program. In the specific case of our group, this will be to do R&D to improve the state of the art for a couple of promising technologies for very fast timing detectors, at the level of 10 picoseconds or better. Our group intends to study and improve upon both the LAPPD MCP-PMT detectors as well as glass mRPCs, both of which have been reported to achieve close to 10 picosecond resolution. Either of these technologies could form the basis for a very high resolution Time-of-Flight detector for particle identification at an EIC. Our studies intend to try to understand and push these technologies beyond the current performance to see where the limitations are. Eventually our goal is to attempt to see if we can achieve sub-10 ps resolution, or determine where the limitations are. Our group fervently believes that by pushing the state of the art in timing technology down below 10 ps, it will make it far easier to build a future large detector system capable of 10 ps resolution. It is important to note that 10 ps is all that is required to achieve the physics program at the EIC, but that any improvement upon that can extend the physics reach at an EIC.

While the Incom MCP-PMTs will be delayed, Argonne has made available a small tile facility to produce 6x6 cm^2 LAPPD MCP-PMTs. The smaller size and higher flexibility to try modifications to the standard LAPPD design are much more conducive to our R&D effort. We propose to work in close collaboration with Argonne to develop MCP-PMTs that have improved performance and better suitability for our EIC applications. The improvements we envision are to modify the window and/or photocathode to increase the sensitivity to UV, which should improve the timing resolution. We will also try different schemes to enable pad readout of the PMTs which may be a preferred option at the EIC. We also propose to try direct deposition of a photocathode, such as CsI or a bialkali, on the top MCP plate and reading out in window-less mode for a CF4 based RICH, similar to what was done in RD2013-4 where that group did the same with a GEM. The ideas developed over the first two years of the proposal will then be used when producing the first adopter Incom LAPPD MCP-PMTs for our final prototype in the third year.

While our proposal is centered on a TOF system for PID, it is important to note that a single photon sensitive detector capable of 10 picosecond timing and with good position resolution can be used in a variety of other applications at the EIC, such as the RICH, Time-of-Propagation detector, or as a the light collector for a calorimeter. Thus, our studies, if approved, could have much wider applicability than detailed in this proposal.

Another promising technology that we intend to pursue is multi-gap Resistive Plate Chambers (mRPC). mRPCs are the leading technology for TOF today, due to their low cost and good performance. Compared to MCP-PMTs, their main advantage is in cost. A large system of mRPC's will certainly be affordable for the EIC, while it is not known yet if that will be the case for MCP-PMTs. The performance of mRPCs has generally never matched that of MCP-PMTs. However, Crispin Williams has measured 16 ps resolution with a 24 gap mRPC [YYY]. In recent discussions with Crispin, he also noted to us privately that he actually expected his detector to achieve 8 ps based on his simulations. He also suggested that the performance could be improved beyond 8 ps by using a heavier gas. Our group intends to reproduce his 16 ps resolution result, and attempt to figure out why the expected 8 ps was not achieved. We will also embark on a simulation of the detailed physics of mRPCs to determine what the limitations are in the timing resolution, and use that as a guide to further development of mRPCs.

During the last committee meeting, UIUC was allocated funds to cover 0.5 FTE for a post-doc, with the other half covered by UIUC. Since then, a search was formed and the post-doc was hired. Ihnjea Choi will start at UIUC with 50% of his time devoted to production and testing of mRPC prototypes, and simulation studies of the physics case for PID at the EIC. UIUC has also allocated undergraduate and graduate student to the simulation studies. Some of their results are included in this note.

Simulation Studies Demonstrating Utility of TOF PID

The UIUC group has embarked on simulations to demonstrate where a TOF PID system contributes in the overall physics program of the EIC, especially with regard to how it fits in relation to other PID detectors, such as a RICH. Essentially, since the RICH detectors need to have high momentum reach, they will necessarily have a relatively high threshold before particles will register in the RICH. For instance, the RICH proposed in RD2011-6 has thresholds of about 4, 15, and 28 GeV for the pi, K, and p, respectively. A TOF system would neatly complement such a RICH detector, provided it had resolution of about 10 ps, which would allow the TOF to cover the lower momenta without taking much of the valuable space. To demonstrate where the TOF contributes, UIUC has looked into the measurement of transverse Collins and IFF spin asymmetries.

Nucleon structure has been studied through semi inclusive deep inelastic scattering (SIDIS) by experiments at CERN, DESY and Jefferson Laboratory. The goal of these measurements was to utilize the additional hadron detected in the final state to decompose the flavor dependence of quark-momentum distributions, quark-helicity distributions and quark transversity distributions. The determination of quark distribution functions from experimental counting rates and spin-dependent asymmetries between counting rates requires as sophisticated analysis of the experimental data using perturbative QCD (pQCD) in the context of the Operator Production Expansion (OPE).

At the present time the extraction of quark distributions from the experimental data is limited by several factors including the limited experimental statistics, limits to the validity of a pQCD based extraction of quark distributions at leading order OPE at the low Q^2 of the available data sets and instrumentation related limitations in particular particle identification capabilities. For transverse momentum dependent (TMD) quark distributions an additional difficulty arises from the still unknown evolution - a subject of lively discourse.

In summary these deficiencies lead to serious shortcomings in the knowledge of quark distributions inside the nucleon: some are completely unknown, some have large uncertainties, many are known only for a limited kinematic range, all present results are subject to un-quantified uncertainties resulting from the low Q^2 of the data sets and/or limitations in experimental capabilities and/or procedures in the analysis (e.g. the use of event generator based purities).

Detailed studies of quark-substructure using SIDIS are planned with new detectors and upgraded beam energy and intensity at Jefferson Laboratory. The measurements scheduled at Jefferson Laboratory will dramatically increase the statistical accuracy of extracted quark distributions and the kinematic coverage in x at low Q^2. High precision SIDIS measurements at high Q^2 at EIC will eliminate uncertainties stemming from the pQCD based data analysis at leading order OPE. The EIC measurements would make possible the first the extraction of quark distributions without un-quantified uncertainties and rigorous tests for related QCD sum-rules. For transverse momentum dependent quark distributions the combined data sets from Jefferson Laboratory and EIC would lead to a quantitative verification of different theoretical approaches for the evolution of TMD distribution- and fragmentation-functions.

In addition to the proposed detector R&D for psTOF for EIC detectors the proponents of this proposal will carry out a systematic study of the impact different options for particle ID in possible EIC detectors will have on the knowledge of quark distribution functions. A graduate student, Yakov Kulinich, and two undergraduate students, Chong Han and David Hjelmstad, have started at UIUC in April 2014 to study the possibility of transversity distribution measurements with psTOF added to an EIC detector. The goal is to establish the feasibility of a physics program that aims at a rigorous extraction of quark- and antiquark-transversity distribution and from this an experimental determination of the tensor charge. The experimental result for the tensor charge then can be compared to the determination of the tensor charge based on lattice QCD.

As a first step transverse spin asymmetries have been added to PYTHIA and a simple response functions for the RICH and TOF detectors was implemented: pion threshold, p_{thresh} > 5 GeV, and a kaon threshold of 15 GeV. TOF pi-K separation up to 6.6 GeV and K-p separation up to 11.1 GeV. A measurement of the tensor charge requires the extraction of transversity distributions at large x. For this reason we chosen to study a psTOF system placed 3.5 m away from the interaction point in the direction of the outgoing hadron beam. The psTOF detector is assumed to cover an angular range from $5 < \theta < 30$ degree with respect to the proton beam for the hadron detected in the final state. For a simple estimate of the statistical significance of a measurement of Collins asymmetries A_{UT} it was assumed that the quark transversity distributions saturate the Soffer limit and that the Collins function reaches the unitarity bound. The resulting Collins asymmetries are shown in Fig. 7. The figure compares the statistical uncertainties for a measurement using the RICH alone and the measurment using the psTOF and the RICH. It can be seen that the presence of the psTOF increases the statistics available at large x significantly and extends the x-range from x~0.65 to x~0.85. The simulation assumes beam momenta of $p_h = 150$ GeV and $p_e = 5$ GeV and an integrated luminosity of $\int Ldt = 12\ fb^{-1}$.

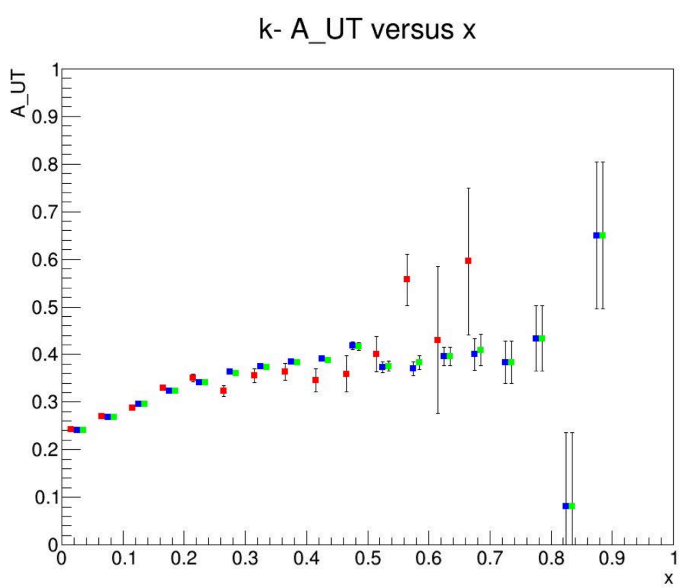

Fig 7: Single transverse spin asymmetries for the Collins/sin($\phi+\phi_S$) moment in SDIS production of negative kaons. The green data points represent the results obtained with PID based on a psTOF system and the forward RICH in the standard detector. The blue data points are the corresponding results for the psTOF system alone and the red data points for the RICH alone. The detectors are assumed to cover the forward region with scattering angles for the observed hadron between $3<\theta_h<30$ degree. Forward angles with respect to the beam axis are important for a measurement of the tensor charge as the tensor charge receives significant contributions from the high x region.

Starting in July, Ihnjea will assist in implementing a GEANT based detector simulations on either the new UIUC campus cluster or the Blue Waters supercomputer at NCSA in Urbana. This study is expected to have final simulation results on quark transversity distributions, including the sensitivity for anti-quark transversity distribution and the strange transversity distribution by the end of 2014. It is then planned to study EIC sensitivities for momentum- and helicity-distributions. Beyond the studies that are already available for momentum- and helicity-dependent distributions we aim to investigate the capabilities at EIC to measure the p_T dependence of distribution functions and fragmentation functions. Nucleon structure has been studied through semi inclusive deep inelastic scattering (SIDIS) by experiments at CERN, DESY and Jefferson Laboratory. The goal of these measurements was to utilize the additional hadron detected in the final state to decompose the flavor dependence of quark-momentum distributions, quark-helicity distributions and quark transversity distributions. The determination of quark distribution functions from experimental counting rates and spin-dependent asymmetries in counting rates requires as sophisticated analysis of the experimental data using perturbative QCD (pQCD) in the context of the Operator Production Expansion (OPE).

TOF PID Research based on the LAPPD MCP-PMT

Since the LAPPD MCP-PMT effort is still fairly new, it is still undergoing rapid improvements. The fact that the project is so new does give us an unique opportunity to contribute to that improvement effort in a way consistent with maximizing it's usefulness for an EIC detector. As mentioned previously, the LAPPD collaboration has developed a procedure to possibly construct cost-effective and large 20x20 cm^2 MCP-PMTs with comparable performance to existing MCP-PMTs. Now the effort is switching to actual commercial production, with SBIR funding for a pilot line to test mass manufacturing techniques at Incom, Inc. These commercial MCP-PMT variants will be available starting sometime in the 2nd year of our proposal.

In the meantime, Argonne has made available their production facility for 6x6 cm^2 LAPPD style MCP-PMT tiles. A picture of the facility is shown in Fig. 1. The facility can produce only one tile at a time, but the smaller size, and the flexibility to more easily try different designs of the MCP-PMTs, are very conducive for doing R&D with these Argonne tiles. We expect to make use of this facility in close collaboration with Argonne to develop the MCP-PMT for our EIC purposes as described in this note, and then work with Incom to implement these changes for the commercially produced MCP-PMTs in the 3rd year of our proposal.

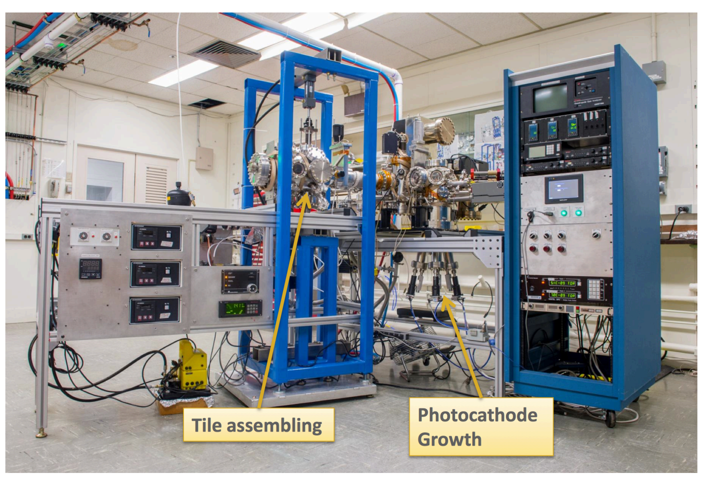

Figure 1: Argonne LAPPD MCP-PMT Tile Production Facility.

The design of the standard LAPPD MCP-PMT is shown in Fig. 2. The green plates in the figure are microcapillary arrays, which are made from borosilicate glass with 25 um holes inclined at 8° angles and with the top and bottom holes lined up but chevron'ed together. These plates are functionalized with a resistive layer and a secondary emission layer using atomic layer deposition. The top and bottom faces are also electrode coated. The grid spacers hold the plates in the correct vertical positions, but also are used to provide the HV potential across the plates. The two plates form the electron multiplication for the MCP, and can achieve gains as high as 10^7, though we expect to run with a gain of 10^6. The bottom window is borosilicate glass and is silk screened to form copper strip anodes. The photocathode window is also borosilicate glass and a CsNa2KSb bialkali photocathode is used. The photocathode has been demonstrated to reach 25% QE at $\lambda \sim 350$ nm. The entire assembly is evacuated, and then compressed together with the indium wire used to seal the glass windows to the side walls. The MCP-PMT is then held together through the vacuum seal.

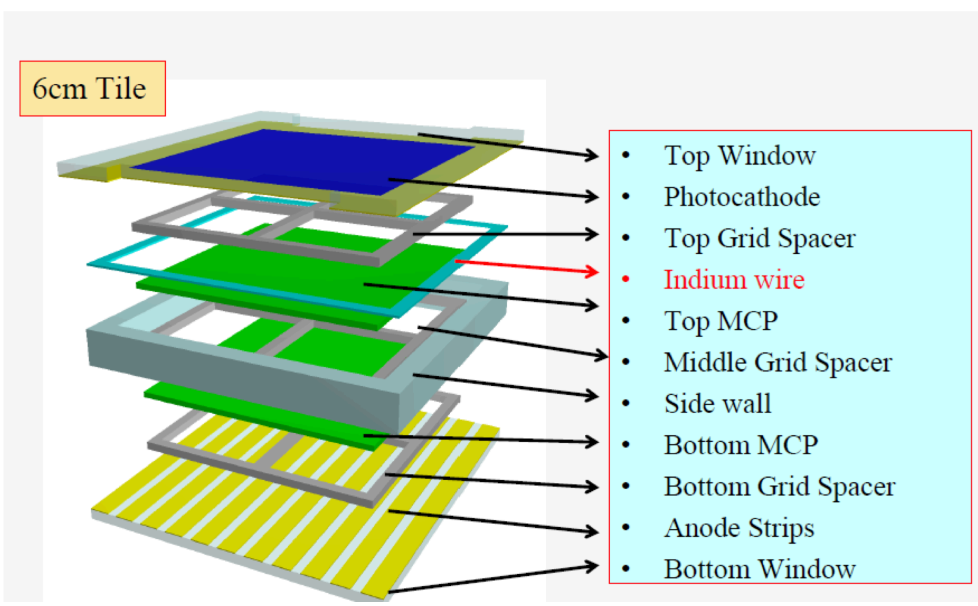

Figure 2: Layers of the LAPPD MCP-PMT, showing the window, the two 10-25 um hole MCPs, and the bottom anode.

To build a TOF device out of an MCP-PMT, one places a solid Cerenkov radiator optically coupled to the MCP-PMT. A schematic picture of the design is shown in Fig. 3. Since the Cerenkov photons are produced promptly, they should arrive at the photocathode within less than a picosecond of each other. This is true for particles at normal incidence, but becomes less true for particles coming in at an angle. One key obstacle to overcome will be determining how to ensure a projective geometry for the MCP-PMT tiles so that particles all arrive at near normal incidence, and this will be studied in detail.

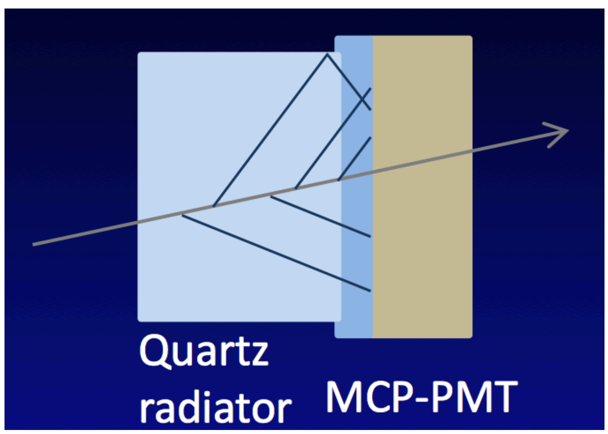

Figure 3: Schematic picture of a direct TOF detector using MCP-PMTs. The radiator provides a prompt light response onto the photocathode of the MCP-PMT.

Research Program with the LAPPD MCP-PMT

While the performance of the LAPPD MCP-PMTs has been reported to be very good, these devices are still so new that we will want to confirm their performance, and also check things that the LAPPD collaboration has been too busy to do. Among the things that our group will check are the time and position resolution, the efficiency, the rate capability, the uniformity, the quiescent noise, the performance in a magnetic field, the aging effects (which are a known problem with other MCP-PMTs), and how radiation hard they are.

The time resolution performance for the LAPPD MCP-PMTs has been reported to be extremely good, with transit time spreads (TTS) of better than 50 ps reported. The ultimate resolution will be a function of the amount of signal, which in our case means the number of photoelectrons generated from the Cerenkov light, and the noise in the MCP-PMT and readout electronics, as well as the analog bandwidth of the electronics and the intrinsic resolution of the electronics itself. The standard LAPPD MCP-PMTs use a borosilicate glass window with a $CsNa_2kSb$ photocathode. While the performance is already very good with this standard design, one can readily improve the performance by going to windows and photocathodes which will capture more of the UV part of the spectrum, since Cerenkov emission is strongest in the UV. In Fig. 4 we show the quantum efficiency curves for a variety of photocathodes. One can see that the QE for the photocathode used by LAPPD, $CsNA_2kSb$ has a sharp cutoff due to the borosilicate (pyrex) window.

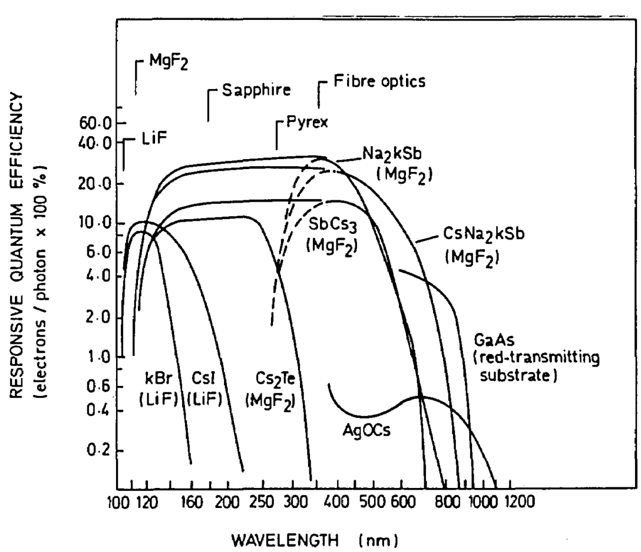

Fig. 4. Example quantum efficiencies for various photocathodes, with the cut-offs for different windows. The dashed lines show the quantum efficiency convoluted with the pyrex cutoff.

Thus, one simple modification to the standard LAPPD design is to change the radiator and/or photocathode in order to produce more photoelectrons. Various combinations of radiators and photocathodes have been evaluated. Some that were looked into we did not list, such as GaN or GaAs, but which may be of interest for other applications. Based on considerations of cost, ease of handling, and performance, a possible option that might be better for the EIC would be a fused silica window with the standard $CsNA_2kSb$ photocathode, since it gives theoretically 40% better performance at reasonable cost.

RadiatorWindow	Thickness (cm)	Photocathode	N.P.E.	σ_t (ps) TTS=50 ps
Borosilicate Glass	1 cm	$CsNA_2kSb$	100	5
Fused Silica	1 cm	$CsNA_2kSb$	250	3.2
MgF2	1 cm	$CsNA_2kSb$	335	2.7
MgF2	1 cm	CsI	316	2.8
CF4	100 cm	$CsNA_2kSb$	72	n/a
CF4	100 cm	CsI	92	n/a

Table 1: The theoretical maximum number of photoelectrons for various Cerenkov Radiator and Photocathode combinations, and the resulting theoretically best possible σ_t. The values for CF4 are for a windowless configuration, where the photocathode is deposited on the top MCP.

We intend to build and evaluate such a configuration in our proposal. While this seems like a small change which does not require much R&D, in fact it should not be underestimated the challenges of sealing the fused silica window. The LAPPD collaboration has actually had their own challenges sealing with the glass windows. Whatever process is chosen for the seal must also be robust enough to work for the much larger 20x20 cm^2 Incom LAPPD tiles. We anticipate many iterations trying different fused silica seals on test setups, and only through close collaboration with Argonne, the rest of the LAPPD collaboration, and BNL Instrumentation will this be successful.

In addition to the technical questions of producing a modification of the LAPPD design, there will likely arise limits as we push down in the timing resolution. Will there be bandwidth or noise limitations in the strip anodes that were not anticipated? Is the electronics capable of keeping up with the improved detector resolution? Is there saturation of charge for very high n.p.e., and does it affect the rate capability? Is the radiator design such that the spread in arrival time of the photons small enough so that it does not contribute to the overall resolution, and if it isn't, can one correct for the spread?

In the last two lines of table 1, we have listed the theoretical maximum number of photoelectrons for operation in window-less mode and immersed in CF4, similar to the RICH proposed in RD2011-6 by Tom Hemmick, but where they use a CsI coated GEM. In the CsI coated GEM this theoretical maximum is reduced by numerous factors to get the realistic n.p.e. From the PHENIX HBD study, they have determined the factors to be:

Optical transparency of mesh	88.5%
Optical transparency of photocathode	81%
Radiator gas transparency	89%
Transport efficiency	80%
Reverse bias and pad threshold	90%

Of the above, the MCP won't have the mesh or reverse bias factors, so that there is a chance a CsI coated MCP-PMT may have a higher p.e. yield. The other factors are currently unknown for MCP-PMTs. Also, the MCP-PMT will have many other advantages. It will have much higher gains (10^6 vs 10^4 for the triple-stack GEM). It won't have problems with gap sparking. It will also have very good timing resolution, of the order of 50 ps per p.e., which will help dramatically with background suppression.

One disadvantage will be that it is much thicker than a triple stack GEM, so that it might only be possible to be used if the Cerenkov light is reflected to the sides out of the acceptance, or if the light is focused on the back wall, as is proposed in RD 2013-4.

Due to these advantages and the possibility that it might be very useful in RICH detectors, our group proposes to try direct photocathode deposition on the top plate of the MCP-PMT. This will be done in the 2nd year. The RD 2013-4 group has proposed depositing a bialkali photocathode on a GEM as a readout for a dual radiator RICH. We will wait to learn of their experience to decide whether to try, in collaboration with them, the $CsNa_2kSb$ photocathode, or whether to use CsI as in the RD 2011-6 proposal.

There will be many questions with this particular part of the program. Does the MCP-PMT operate well in CF4? Normally it is operated only in vacuum. Will the presence of the photocathodes create additional noise? Will it interfere with the electron multiplication process? What will happen because there is photocathode material in the pores? All these questions will hopefully be addressed by our R&D.

Another modification that would be important is to generalize the signal geometry so that we could use whatever is most appropriate for the application. Currently the standard LAPPD design uses strip line anodes which are created by silk-screening on top of borosilicate glass plate. However, for a RICH one might prefer pad readout instead of strips, and it is difficult to bring the signals out with using vias or without crosstalk if the signals are brought out the sides. In addition, clever readout configurations have been proposed in RD2011-6 which save channel count without sacrificing performance in spatial resolution. It would be beneficial to be able to generalize the signal plane to be able to use whatever is best, rather than be forced to use strip line readout.

We propose a couple of possibilities that we will try. One is to use a high resistivity electrode for the anode, and then use cathodes on a PCB on the outside of the bottom window of the MCP-PMT to capacitively pick up the fast signals which propagate through the electrode. Graphite has been used in mRPCs as the electrode for this purpose, but other electrode materials could be considered, depending on whether the material causes a bad reaction with something inside the MCP-PMT housing. There may be several issues with this approach. The induced signal might not have the same performance as the directly collected charge signal. In any case, the bottom window will have to be made thinner in order to improve the signal performance by putting the cathodes closer to the anode. Another issue is that by going to pad readout, one may change the signal characteristics in such as way as to degrade the timing performance.

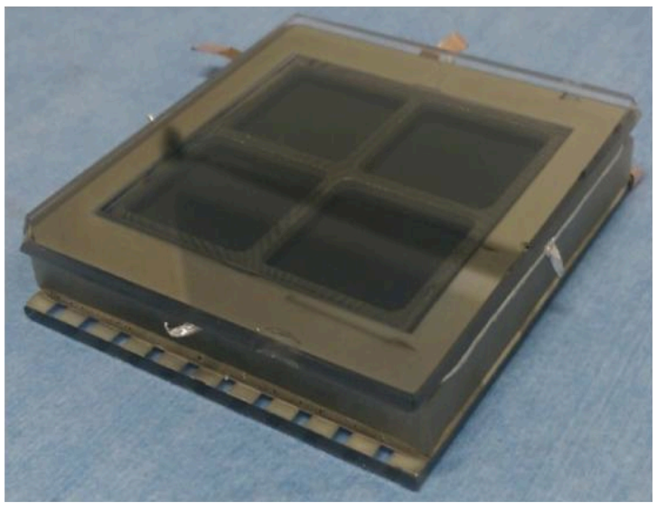

Fig 5. Picture of a standard 6x6 cm^2 Argonne LAPPD MCP-PMT, with the strip anodes shown on the bottom plate.

A second alternative is to replace the bottom borosilicate window with a rigid PCB. One can then put any geometry one wanted. Here the problem will come from trying to seal the device, which will require a new round of R&D. Also, even if one is successful at sealing the 6x6 cm^2 device, one will ultimately have to use a process that can seal the 20x20 cm^2 MCP-PMTs, while being rigid and strong enough over that much larger size.

TOF PID Research based on the Multi-Gap Resistive Plate Chambers

Our second major effort will involve pushing the performance of mRPCs, which have achieved ~50-100 ps resolution in Alice, Star, and PHENIX, over large areas (175 m^2 in the case of Alice). However, by going to smaller gap sizes (250 um to 160 um), and doubling the number of gaps from 12 to 24, and reducing the thickness of the glass, Crispin Williams, et al have shown that a resolution as good as 16 ps is achievable. We hope to be able to reproduce this result. A picture of a prototype 24 gap mRPC is shown in Fig. 6. These devices are made of float glass, fishing line, PCB, and graphite, so they are fairly cheap to construct.

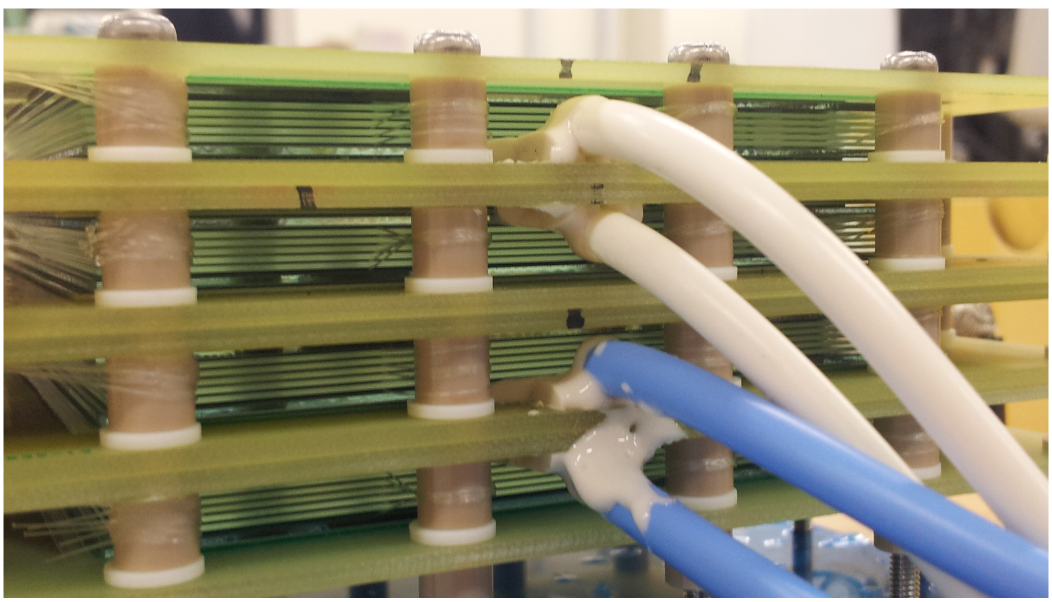

Fig. 6: Prototype mRPC with 24 gaps, 150 um each.

In principle, the device specified by Crispin should achieve 8 ps resolution. After reproducing Crispin's result, we will embark on a study to determine what the limiting factors in the resolution. One simple possibility is that they did not correct for the hit position on the cathode strips. Another possibility is that they were limited by their electronics, or the noise levels of their system.

In addition to reproducing the 16 ps resolution result, we have ideas for perhaps improving the resolution even further. One possibility might be to identify a gas which can produce more initial ionization electrons, since these are one of the main contributions to the resolution. In table 2, we have listed the properties of some gases, where n_p is the number of primary ionization electrons. These initial electrons may have enough energy before acceleration by field to create more electron-ion pairs. The total of the n_p and secondary electron creation is n_t. Here one can see why i-C4H10 is used in mRPCs. Perhaps an alternative, better gas for timing is Xe, since it has a large number of initial electrons created? However, Xenon is expensive, so as part of our R&D we will research other possible gases to find one that is a good combination of cost and performance.

Gas	Z	A	Density 10^{-3} (g/cm^3)	E_x (eV)	E_i (eV)	w_i (eV)	$[dE/dx]_{mip}$ (keV cm^{-1})	n_p (cm^{-1}) N.T.P	n_t (cm^{-1}) N.T.P.	Radiation Length (m)
He	2	2	0.178	19.8	24.5	41	0.32	4.2	8	745
Ar	18	39.9	1.782	11.6	15.7	26	2.44	23	94	110
Ne	10	20.2	0.90	16.6 7	21.56	36.3	1.56	12	43	345
Xe	54	131.3	5.86	8.4	12.1	22	6.76	44	307	15
CF_4	42	88	3.93	12.5	15.9	54	7	51	100	92.4
DME	26	46	2.2	6.4	10.0	23.9	3.9	55	160	222
CO_2	22	44	1.98	5.2	13.7	33	3.01	35.5	91	183
CH_4	10	16	0.71	9.8	15.2	28	1.48	25	53	646
C_2H_6	18	30	1.34	8.7	11.7	27	1.15	41	111	340
i-C_4H_{10}	34	58	2.59	6.5	10.6	23	5.93	84	195	169

Table 2: Physical properties of gases at 20° C and 760 Torr.

Since the parameter space is very large, we intend to develop a full simulation of the physical process of avalanche creation in small gas gaps in order to guide our R&D. The processes are well understood, and there are a few simulations that have been done before, but to our knowledge no one has undertaken a systematic study to determine the best combination of factors that will improve the timing resolution. We will build on the pre-existing work and initiate a comprehensive study to determine the factors that contribute to the timing, and hopefully identify a configuration in the parameter space that maximizes the timing resolution.

Yet another possibility we have considered for improving mRPCs is to replace the glass material with another insulator. We have considered mylar and kapton. The issues here will be that we might have to find some way to match the total volume resistivity of glass. A simple way might be to tune the thickness so that it has similar total volume resistance as glass, but most likely we will have to find a way to dope the mylar since the resistivities are so much higher in mylar and kapton. The advantage of going to different materials is that one can make them much thinner, thus bringing the signals closer to the cathode pickup and allowing one to make many more gaps in the same volume. It may also reduce the cost, and be easier to produce, since one doesn't have to worry about glass breakage.

Fast Electronics

The technical challenge of developing a detector capable of 10 picosecond resolution is great, but so has been the challenge of designing cost-effective, low power electronics that is capable of measuring at that extreme resolution. Of course the detector is useless without the electronics to read it out. Currently, much of the research is based on using fast waveform digitizing electronics for fast timing readout. By fast, we usually mean on the level of 5 GSa/s or higher. Usually they incorporate switched capacitor array (SCA) networks and delay line loops to produce fast, correctible timing, and amplitude digitization. We have successfully tested DRS4 based boards to have a resolution of just 8 ps/sample, and there are reports that newer revisions of the DRS4 evaluation board achieves 1 ps/sample resolution. One issue here might be that the input analog bandwidth of the DRS4 is only about 750 MHz, which might be an ultimate limit to the resolution one can achieve. We will measure that and evaluate whether this is one of fundamental limitations.

In addition to the digitizer, for the mRPC one needs a high analog bandwidth differential preamp, or the order of a GHz, with gains of about 10 for the mRPC signals. On the commercial market the only ones available draw about 1 Amp. Over a detector system of 10K channels, this will amount to 10 kA, which is far too hot. We will attempt to develop a low current, high analog bandwidth preamp for use in fast timing applications, which is something that does not readily exist today.

Summary Description of Proposed Studies

Our program of R&D is intended to produce, within 2-3 years time, a working demonstration of two technologies which can achieve at least 10 ps timing resolution, and hopefully even better than 10 ps. Our studies are also intended to further the understanding of the fundamental limitations to getting to 1 ps resolution. These studies will be necessary for the next generation of timing detectors that might be required at future facilities. Our goal in pushing the limits of the timing technology is that it will make it much easier to achieve the required goal of 10 ps for the EIC. Thus, by pushing the limits of the resolution down to sub-10 ps levels, we believe that we will gain the knowledge and experience required to make building large-scale detector systems capable of 10 ps resolution, thus making it far easier later when the large scale detector needs to be constructed.

To do this, we will further the state of the art in mRPC technology, which promises to have different advantages and disadvantages from MCP-PMTs, particularly in the total cost and the ability to operate in the solenoidal magnetic field of a barrel detector. Simultaneously, we plan to take advantage of the enormous flexibility of the small tile production facility at Argonne, which is capable of producing small batches of very high performance and customized 6x6 cm^2 MCP-PMTs to study variations in the design of the MCP-PMTs that would optimize it for uses at the EIC. The flexibility of the Argonne facility allows us to quickly and more cheaply check our ideas for improvements. This knowledge will ultimately feed into improvements for the design of the commercially produced 20x20 cm^2 tiles from Incom. While we have proposed these studies for a TOF system for PID, a single photon sensitive detector capable of 10 picosecond timing and with good position resolution can be used in a variety of other applications at the EIC, such as for a RICH, Time-of-Propagation detector, or as a start counter. Thus, our studies, if approved, could have much wider applicability than detailed in this proposal. The following details our 3-Year plan of study, including the timeline for when we expect to have these studies done.

Year 1 Plans

In the first year we propose an expansive plan that will allow us to gain familiarity and start studies to improve the performance of the two types of fast timing detectors we have identified as promising to study. We will start with 6x6 cm^2 versions of the LAPPD MCP-PMTs from Argonne, as well as build the first U.S. made versions of glass mRPCs that can achieve 16 ps resolution or better. In both cases we will work further to improve the timing performance towards our needs for the EIC, and studying systematically the limitations that prevent going below 10 ps. We expect to have two to three iterations of devices during this first year, as discussed below.

The major milestones we hope to achieve in the first year starting from the 2015 fiscal year, along with the responsible parties, are:

- (Argonne, BNL, UMass) Acquire a couple of the standard LAPPD MCP-PMTs from Argonne's small tile facility, built with borosilicate glass and bialkali photocathode. These will be used to familiarize ourselves with operations and readout of the MCP-PMTs, and characterize their performance as a baseline for future studies to see if we can improve upon them for our EIC needs. The specific characterization studies that can be done in this first year are:
    - Timing and Position Resolution: This will be done initially with laser studies and then from cosmic ray studies, and varying the HV.
    - Uniformity: We want to demonstrate uniform effectiveness across the detectors. This can be done with laser scans and cosmic rays.
    - Quiescent Noise: LAPPD claims less than 0.1 Hz/cm^2 of background noise. We want to check this and ensure that they are below the rate needed at an EIC detector.
    - Rate Capability: Initial studies will be done with a laser, though final studies will have to be done in test beam.

  - Operation in Magnetic Field: We want to determine the effects of a magnetic field on the operation of the MCP-PMT, particularly for the case where the field is transverse to the pore axis. Can the effects be mitigated by increasing the HV bias on the tube? This testing can be done at the test magnet facility at BNL or Argonne.

  - Aging: We want to determine the aging characteristics of the LAPPD MCP-PMTs. Since this is potentially destructive to the MCP-PMT, we may perhaps defer this test to the LAPPD collaboration. It is of high enough importance though that we would like to address this issue as early as possible.

  - Radiation Hardness: Study the resistance to radiation damage, including high particle rates as well as susceptibility to thermal neutrons. As in the aging studies, while these are destructive, it is important to try to characterize this earlier rather than later.

- (UIUC, BNL) Build and characterize the performance of a relatively standard 24 gap glass mRPC capable of achieving 16 ps resolution. These studies build on the infrastructure and expertise at UIUC from their experience building the RPC muon trigger for PHENIX. The same characterization studies as described for the MCP-PMTs will be done.

- (Argonne, Yale) Replacement of the LAPPD strip-line anodes with alternatives that allow for pad readout, using either the graphite anode with external capacitive pad pickup, or by using a PCB. In the first approach the main issue is whether the signal quality will be maintained, and in the second approach the main issue is whether one can maintain a good seal.

- (Argonne, BNL, UMass) Replacement of LAPPD MCP-PMT faceplate with fused silica. This should increase the p.e. yield by a factor of 2.5, and we will study whether this improves the timing resolution by expected statistical factor. Here the main technical issue will be with achieving a good seal using the new material.

- (UIUC, UMass, BNL, Yale) Study and simulate the primary physics channels which we think are the most interesting that would be enabled by particle identification. Initial work has been done at UIUC simulating the capability of measuring the transversity distribution function at high Bjorken-x in the proton using measurements of the IFF and Collins asymmetries. We want to also broaden the studies to include measurements of kaons to determine Δs in nuclei, as well as complete the necessary studies to ensure that our design can accommodate as much of the interesting physics where particle identification is required at the EIC. We will also evaluate the capability of TOF, in addition to dE/dx in a TPC, to improve electron identification.

- (UIUC, Howard, BNL) Come up with a TOF PID detector design that satisfies these physics requirements. In the case of the MCP-PMTs, this includes the size and shape of the Cerenkov radiators, and how to enable a projective geometry from the flat Incom 20x20 cm^2 tiles. We will also calculate and optimize the expected number of photoelectrons from a typical particle to maximize the performance of the timing measurement, within reasonable limits on the cost.

- (Howard, UIUC, BNL) A graduate student at Howard will be dedicated to creating a simulation of all the detailed evolution of the signal generation in the mRPC, from the initial electron-ion pair creation to the electron avalanche and finally signal generation in the cathodes. These studies will be used to guide further development of mRPC design, as we will be able to vary the gas parameters, the gap thicknesses, the glass resistivity, and substituting different materials for the glass, to determine how they affect performance. These simulations will allow for a much more informed and well guided R&D program as we try to improve the mRPC to sub-10 ps timing resolution levels.

Year 2 Plans

In the second year we hope to have identified many of the problems limiting the resolution and gotten a prototype that can do better than 10 ps. We will work in close collaboration with Argonne in trying different modifications to the standard LAPPD design to better suit our EIC goals, to improve the performance, and to overcome whatever obstacles we can identify. Given the limited time and equipment for producing MCP-PMTs, as well as the manpower available, we will have to make informed decisions about what to best study since only a few iterations will be possible. How successful we are will depend on whether the variations we try lead to increased performance or ease of use.

Below, we summarize our milestones for the second year, along with some of the major concerns for us to test:

- (All) Test of MCP-PMTs and mRPCs at the Fermilab test beam facility. Here the rate dependence can be fully studied, and check the realistic performance of the detector. Also, since the beam rates are much higher than with cosmics, we can do high statistics, systematic studies of the uniformity, beam angle, HV, and gas dependence.

- (UMass, BNL) In addition to continuing the development efforts of the previous year, we will further explore the potential of the MCP-PMTs by trying the CsNa2KSb or CsI photocathodes deposited directly on the front MCP. It is also possible that we may explore other studies that we come up with during this second year.

- (UIUC, UMass, BNL, Yale) Detailed studies of the physics motivation for PID at EIC using TOF, including at least one example of the TOF integrated into one of the proposed EIC detectors with full Geant simulation, to understand if there any subtle problems that need to be solved, and also how the detectors integrate with each other. An example of a subtle problem we hope to have resolved with these studies is to have a scheme to determine the start time for the event in a robust manner.

- (UMass) Work in collaboration with Incom to implement the manufacturing changes to the standard LAPPD design that we deem are important for the EIC final detector.

Year 3 Plans

In year 3, we envision taking the knowledge gained from the first two years to inform us on the final design for the two technology options we are exploring in this proposal, and final prototypes will be made for testing at the Fermilab test beam facility.

In the case of the MCP-PMTs, we hope to build this prototype using the commercially built Incom versions of the LAPPD MCP-PMT. It is important to test the commercially built variation of these LAPPD MCP-PMTs since only they have the possibility of being cost-effective enough to be considered in the final EIC detector. Incom has just received the SBIR funding for this pilot line production in May 2014, and expects to set up the pilot line this year so that the tiles will be available in late 2015. Accounting for the usual delays and allowing time for potential problems with the initial batches to be solved, we expect to purchase the Incom tiles in Fall 2016. We expect these Incom tiles to incorporate the modifications and improvements for our EIC needs that we will develop in the first two years of this proposal.

Since this will be the first time that these tiles have been tested, we will have to characterize them as well. In particular, we will proceed to test the Incom LAPPD tiles for the main issues that we have identified, such as the timing capabilities, the rate capabilities, the aging effects, and the ability to operate in a magnetic field.

The milestones for the third year are the following:

- (Argonne, BNL, UMass, Yale) Produce a final prototype of the TOF detector using the Incom LAPPD MCP-PMTs.
- (UIUC, BNL, Howard) Produce final prototypes of the mRPC detectors.
- (All) Test all final prototypes in the Fermilab test beam for a final characterization of their performance.

Budget

We are very fortunate to be able to collaborate with Argonne, since most of the (expensive) materials needed to produce MCP-PMTs will be supported by them. We believe the main ingredient that will be needed for a successful project is the manpower to very deliberately try different things in the design and construction of the MCP-PMTs, such as different ways of sealing, testing different photocathodes, trying different readout geometries, etc. Thus, included in our budget are cost-shared post-doc salaries, split between UIUC, UMass, and Yale, with each post-doc contributing half their time to this project. A graduate student is requested to work on detector simulations at Howard. The post-doc's are expected to collaborate closely with the Argonne in MCP-PMT design modifications, and may need to spend significant time in the tile production facility, at the test beam, and wherever the testing equipment is situated. In the 2nd year we expect the UMass-Amherst post-doc to collaborate closely with Incom to work on the manufacturing process for the MCP-PMTs with the design based on our R&D work, since we expect differences from the standard LAPPD design.

For the amount of time expected from the collaborators that has not been funded by the EIC R&D program, we roughly expect the following. From the BNL group, we expect Mickey to spend ~50% of his time on this project. Thomas works in the Instrumentation group at BNL and is the local expert on lasers PMTs, and will spend a few months helping us to characterize the MCP-PMTs along with the UMass post-doc. Bob Azmoun is the expert who characterized CsI GEMs for the PHENIX HBD, and will dedicate a couple of months characterizing the MCP-PMTs when we coat them, along with the UMass post-doc. Andrey will spend a few months on the design and layout of high analog bandwidth preamps. Eric, Edward, and Craig have decades of detector experience between them and will be expected to be generous god-fathers with their knowledge. UIUC will provide additional students to support the project; at the moment this consists of one graduate student and two undergraduates. Richard and Nikolai, along with John, will oversee the Yale post-doc. Argonne will oversee all of the MCP-PMT small tile production.

The requested budget is given in the next page.

		Fiscal Year 2014		Fiscal Year 2015		Fiscal Year 2016
	Year0	**Year1**		**Year 2**		**Year 3**
	Spring	Fall	Spring	Fall	Spring	Fall
Personnel						
0.5 FTE UIUC post-doc	$60,000		$60,000		$60,000	
0.5 FTE Umass post-doc		$60,000		$60,000		
0.5 FTE Yale post-doc			$60,000		$60,000	
1.0 FTE Howard grad student		$30,000		$30,000		$30,000
Travel Costs						
Travel		$8,000	$8,000	$8,000	$8,000	$8,000
Beam Test (FNAL)				$15,000		$15,000
Equipment						
DRS4 Readout Boards		$16,000				
GHz Preamplifier Boards		$5,000				
mRPC Prototype Materials		$20,000		$20,000		
Argonne LAPPD bare 6x6cm^2 MCPs			$2,000			
Incom LAPPD MCP-PMTs					$50,000	
Totals	$60,000	$139,000	$130,000	$133,000	$178,000	$53,000